DESIGN TOOLS FOR PERFORMANCE ASSESSMENT OF FIGHTER AIRCRAFT INCORPORATING NEW TECHNOLOGIES

Anthony Kutschera*, Peter M. Render†
Department of Aeronautical and Automotive Engineering and Transport Studies
Loughborough University
Loughborough, Leicestershire LE11 3TU
United Kingdom

Abstract

The performance assessment of modern fighter aircraft has been the subject of considerable research in recent years. A new metric called Nodal Manoeuvre Analysis has been proposed, which allows performance assessment of new technologies to be carried out during the conceptual/preliminary design stages of an aircraft. This paper seeks to demonstrate the uses of the Nodal Manoeuvre Analysis metric by considering three case studies. These studies assess the changes in performance of a baseline aircraft in a vertical turn manoeuvre, when new technology is incorporated. The technologies are 1) an increase in thrust, 2) a reduction in weight, and 3) the incorporation of Thrust Vectoring and Post Stall Manoeuvrability. Through these studies, it is shown that Nodal Manoeuvre Analysis can quantify the advantages/disadvantages of incorporating new technology into the design.

Nomenclature

AoA	Angle of Attack
AFFTC	Air Force Flight Test Center
BVR	Beyond Visual Range
CCT	Combat Cycle Time
C_L	Lift Coefficient
D	Drag
DoF	Degree of Freedom
ITR	Instantaneous Turn Rate
L	Lift
NMA	Nodal Manoeuvre Analysis
n_z	Normal Load Factor
P_S	Specific Excess Power
PSM	Post Stall Manoeuvrability
S	Wing Reference Area
SEP	Specific Excess Power
stsl	Static Thrust at Sea Level
t	Time
T	Thrust
TVC	Thrust Vector Control
V	Velocity
W	Weight
WVR	Within Visual Range
α	Angle of Attack

* Research Assistant, GradRAeS, Member AIAA
† Senior Lecturer, MRAeS, Member AIAA

Introduction

There is a distinct need for the implications of new technologies such as Thrust Vector Control (TVC) and Post Stall Manoeuvrability (PSM) to be known early on in the design stage. Experimental projects such as the X-31a, F-18 HARV (High Alpha Research Vehicle) and the F-16 MATV (Multi Axis Thrust Vectoring) have proven the technology. In fact the X-31a project incorporated simulated combat between the X-31a and an F/A-18. According to Smith[1], this showed that with the TVC/PSM, the X-31a gained an overwhelming combat advantage in a one-on-one scenario. With thrust vector control and post stall manoeuvrability now becoming an operational capability with aircraft such as the F-22 and Su-27/30/35 etc., there is a requirement to be able to assess future concepts so that they can be designed to surpass the performance of likely threats. The connotations of TVC and PSM need to be assessed at the early stages of design, for example when comparing conceptual designs. Because of this, the amount of data known about the aircraft will be limited. Also, TVC and PSM are specific examples of new technologies. In general, any new technologies need to be assessed, and it is possible that existing methods do not allow this.

Over the last decade, there has been much discussion about the types of metric that can be used for the assessment of aircraft performance. Bitten[2] discusses the differences between performance, manoeuvrability and agility metrics. Performance relates to the state variables of the aircraft, for example velocity. Manoeuvrability relates to the time differential of the aircraft state (for this example, acceleration). Agility relates to the time differential of manoeuvrability (for this example, rate of change of acceleration). It is the authors' basic view that control power dominates the agility and controllability of a fighter, whereas simple terms like speed, load factor limit and thrust to weight ratio (T/W) dominate the performance. As aircraft develop to become more agile and manoeuvre closer to physical limits, it is agility (and with it transient response) that becomes more important. Different agility metrics have been proposed to help quantify the capability of aircraft designs, including those suggested by Eidetics International[3] and MBB[4]. Three components of agility are defined in both metrics. These are axial, pitch and torsional agility, which relate to time rate of change of axial load factor, time rate of change of normal load factor, and stability axis roll acceleration, respectively.

Currently there is more interest in agility metrics than in performance metrics. Agility metrics are very useful in describing the ability of the aircraft to move quickly and change state. Comparing two aircraft will easily show that

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one is more *agile* than another. However, there are two problems with agility metrics. One is that these metrics do not give a physical feel of the overall combat situation to the designer, tactician or pilot. Knowing that an aircraft can pull a given load factor faster than the adversary, does not necessarily mean an advantage is conferred. For a simplistic example, a large bomber could be designed with such large control power that its pitch acceleration would be greater than a fighter, and hence its pitch agility would be greater. However, its much lower T/W ratio would mean that it loses energy more quickly than the fighter. This would give away the advantage gained by the bomber in the first seconds of manoeuvring, and eventually lead to a shoot solution for the fighter. According to Bitten[2], the Air Force Flight Test Center (AFFTC) emphasise that it is tactically relevant to obtain a desired final state for the aircraft. Factors like the time to pitch to maximum load factor do not tell the designer about the final state of the aircraft. Also, agility metrics do not allow the designer the ability to assess the performance in relation to air combat. This is demonstrated by considering the above example of the bomber. Its superior rate of pitch acceleration does not confer an advantage in combat, but by considering a pitch agility metric, an advantage could be implied.

The second problem is that agility metrics do not allow the conceptual designer to assess the aircraft. Accurate values of control derivatives cannot be known during conceptual and preliminary design[5]. However, agility metrics are important much later in the design, in order to assess the agility of the aircraft, and to ensure that it has enough control power. This will mean that the aircraft is more controllable and will have superior trackability. Reference 6 states that it has been shown that there is a real combat payoff for a high transient response capability, and hence agility is very important.

Reference 2 states that 'defining a metric that uses the time to achieve a relative state change as a measure of performance incorporates the initial state conditions, the rates affected by manoeuvrability, and the accelerations affected by agility. This is termed functional agility by the AFFTC'. This can basically be interpreted as a requirement to look at closed loop tasks, not simply instantaneous performance, or agility.

As will be discussed in the following section, performance metrics do not fully assess new technologies. The limitations in the performance and agility metrics, and the non existence of manoeuvrability metrics means that the conceptual designer is left with no suitable tools in defining the changes that these technologies will bring. This paper addresses the problem and considers a new metric that has been developed called Nodal Manoeuvre Analysis, which assesses functional agility. The assessment of the metric is done through a set of case studies.

The Need for Nodal Manoeuvre Analysis

Kutschera[7] discusses in detail the lack of suitable tools for the conceptual designer to evaluate advanced technologies such as TVC/PSM. Through a literature survey, the study identified over thirty metrics. The suitability of these metrics was discussed with industry and combat pilots. Based on these discussions, Kutschera chose to analyse six metrics.

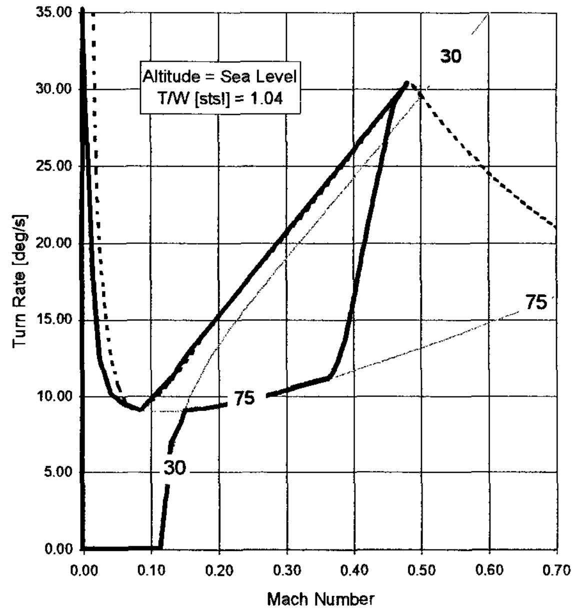

Figure 1 - Post Stall Boundary Shown on a Turn Rate Plot.

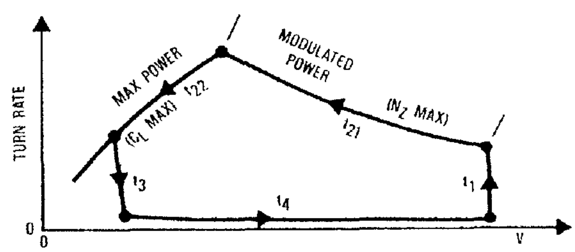

Figure 2 - Concept of CCT.

It was found from the literature review that manoeuvres which are evaluated should consist of closed loop tasks, for example, pitch to a given load factor, not simply pitch to maximum load factor. Since the maximum load factor may vary between aircraft, it is more useful to use a specific load factor, and hence a closed loop task.

The paper shows that metrics such as the turn rate plot can have post stall envelopes added to them, as shown in Figure 1. The figure shows two thin grey lines which are lines of constant AoA (30° and 75°). It also shows a black dashed line which is the Instantaneous Turn Rate (ITR) line. Finally, the thick solid line shows the post stall boundary, constructed from looking at the best possible capability of the aircraft (see Reference 7). The aircraft must be within the thick black line to be able to obtain a post stall AoA. However, these plots only show what is happening in a particular instant during a manoeuvre. In addition, the plots do not assess a closed loop manoeuvre. The same comments also apply to energy manoeuvrability diagrams.

Since existing performance metrics fail to help advanced aircraft assessment, existing functional metrics can be considered. An example of a closed loop metric, discussed in Reference 7, is the Combat Cycle Time (CCT) (this is shown graphically in Figure 2). The CCT is defined as the sum of the times taken to pitch to maximum load factor (t_1), turn

through a heading change of 180° at the ITR (t_{21} + t_{22}), pitch down to 1g (t_3) and accelerate back to the original energy level (t_4). Although this metric includes the time taken to return to the original energy state, it does not consider the position (firing opportunities) of the aircraft.

The definition of the CCT also limits the aircraft manoeuvre to reversing the flight path. Consider the following. The pilot would like to bring the weapons to bear on the enemy by pointing the nose (that is pitching to increased AoA) during the CCT. If the desired AoA is greater than the stall AoA, the turn rate will be reduced, because lift is reduced. This means that reversing the flight path will take longer. Also, because the aircraft will lose energy more quickly while at elevated AoA, the recovery time in the last segment of the CCT will be longer. Although the pilot will have gained a shoot opportunity, the measure of merit will be worse than if the aircraft had followed the original CCT manoeuvre. Hence a full analysis for technology such as TVC/PSM cannot be completed with the CCT metric.

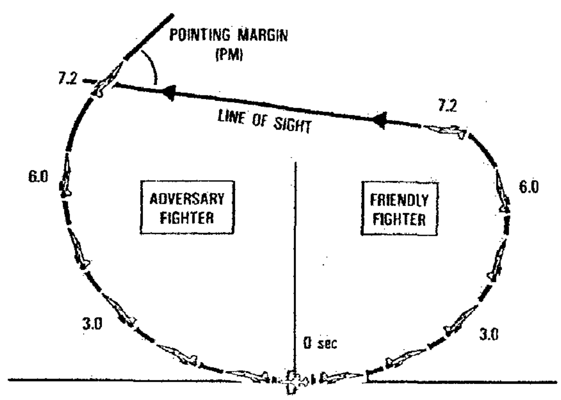

Figure 3 - Definition of Pointing Margin.

Another functional metric, the Pointing Margin, was found to have the most potential. This metric considers two aircraft that have just passed each other and are trying to turn as hard as possible to bear their weapons on the enemy. In Figure 3, the friendly fighter is equipped with TVC/PSM and can point at the enemy aircraft first. The Pointing Margin angle (shown as PM in Figure 3) is used as the measure of merit. However, this metric does not consider variables such as energy, and it depends upon a standard enemy manoeuvre, meaning that absolute performance can not be supplied for an aircraft.

Existing metrics do not really allow new technologies to be assessed at the conceptual design phase. To overcome these problems, a new metric was developed in Reference 7, called Nodal Manoeuvre Analysis (NMA).

Nodal Manoeuvre Analysis

It is of interest to the pilot and hence designer, how quickly the aircraft state can be changed. Questions like, 'How easy is it to manoeuvre the aircraft to a given position with a given direction?', 'How long does it take to get there?', 'How much energy will be expended?' and 'What is the final energy rate?', need to be answered. NMA was developed by considering these questions. Initially, it was thought that the manoeuvres tested should have the objective of getting the aircraft to aim at a given point. However, there are problems with this approach, such as how far away that point should be and should the point move, to simulate an enemy aircraft. For this reason, the objective was altered to get the aircraft to complete a body axis heading change, so that it is aiming in a given plane, for example the vertical plane. The performance is not only limited to the vertical plane, and other planes should be examined. For a fuller assessment, there are also many more combat realistic manoeuvres that should be considered, for example horizontal turn reversal, and axial acceleration. The assessment of the aircraft is done by measuring parameters like time taken to complete the manoeuvre, turn diameter, and energy bleed rate at the end of the manoeuvre. The results are displayed in the altitude-velocity domain, to allow the designer to see quickly where, for example, the elapsed time of the manoeuvre is a minimum. The ability to assess different manoeuvres, in different planes, allows the designer to assess the performance of the aircraft with relevance to air combat.

To illustrate the concept of NMA, this paper considers only one closed loop manoeuvre. This is a 180° degree, body axis heading change, in the vertical plane. The aircraft starts at a given altitude and velocity at 1g normal loading. Then it pitches up to attain AoA for ITR. The aircraft continues to turn until it gets to a point where pitching to the maximum AoA would mean that the target is acquired. At this point, the aircraft does pitch up, and when the angular difference between the body axis and the target is zero, then the manoeuvre is said to be complete. A typical NMA plot is shown in Figure 4, where the contours show the elapsed time in seconds for the aircraft to complete the heading change.

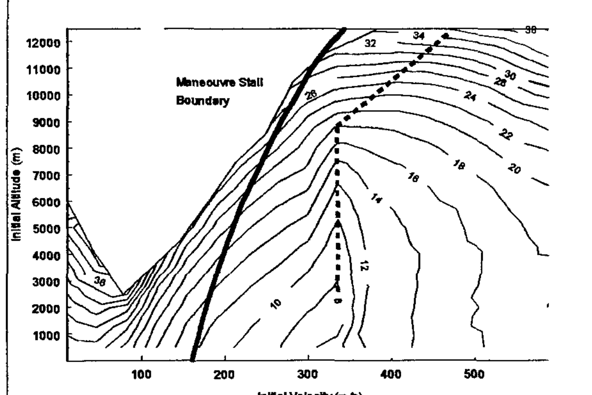

Figure 4 - Time in Seconds to Complete Turn Reversal.

The altitude and velocity axes indicate the initial conditions of the aircraft before the manoeuvre is started. Also shown on the plot are two lines and a boundary. The white area, labelled 'Manoeuvre Stall Boundary' is where an aircraft with initial conditions in this area would stall at some stage during the manoeuvre, and would not be capable of pulling the nose over to point and complete the manoeuvre, without first pitching down to gain speed. The thick black line shows the Corner Velocity in the horizontal plane. Traditionally, this speed is referred to as being where the aircraft is most manoeuvrable since it will have its maximum ITR at this speed. The dashed line shows the best velocity for any given

altitude, to minimise the turn reversal time. Notice the difference between the two lines. This is due to one referring to instantaneous performance, and one referring to a more realistic closed loop manoeuvre.

In principle, any dynamic model of the aircraft of interest can be used for NMA. For the present study, it has been assumed that the amount of data available to the designer is limited to basic geometric data, standard engine data and data derived from the geometry such as weight, lift, drag, etc. It is unlikely that aerodynamic stability derivatives will be known, so it has been deemed acceptable to use a reduced order aircraft model. The model used was reduced to 2 Degrees of Freedom (DoF) with quasi bank freedom. The model was allowed to rotate about the velocity vector and hence turn in the horizontal plane, but the roll response of the model was not modelled. Also, sensitivity analysis showed that pitch response does not have a great effect on final aircraft state variables, and so a very accurate assessment of pitch control derivatives was not required.

The accuracy of the reduced order model was compared with a full 6 DoF non-linear model of the F/A-18a which used unclassified data. Typical accuracy of the reduced order model was such that it was within 5-10% of the full order model, based on a manoeuvre where the objective was to achieve a flight path angle of 90°. For longer manoeuvres, which were not so dependant upon pitch response, the accuracy was improved to less than 5% error.

When using NMA, the designer has to be satisfied that the accuracy of the model being used is acceptable. It should be realised that the outputs will only be as accurate as the inputs provided. If the model used were very inaccurate, then the results of the NMA would also be inaccurate. Any conclusions that were then drawn would be at the discretion of the user executing the analysis.

It should be realised that NMA only provides analysis of the performance of the airframe with initial conditions of speed and altitude. This information is useful for Within Visual Range (WVR) or Beyond Visual Range (BVR) analysis. For WVR analysis, terms such as turn diameter, and turn time are of importance, for BVR, it is turn sustainability (energy usage) which is of importance. Currently, inclusion of a weapons system has not been considered. However, it is suggested that NMA could be adapted to include a weapons system, although this is currently outside the scope of this project. Note that NMA allows the user to use as simple or as complex an aircraft model as required by the analyst. This flexibility, together with the capability to assess performance in WVR and BVR, clearly and concisely using variables that relate directly to combat, gives Nodal Manoeuvre Analysis the potential to be a very powerful tool.

Case Studies

This paper will use the NMA metric for case studies to assess the use of three types of advanced technology. These will be compared to a baseline aircraft, the F/A-18a.

The case studies consider the following three advanced technologies. 1) The use of advanced engines. The F-404-400 engines used on the F/A-18a have a thrust to engine weight ratio of about 5.0:1 (dry). Using advanced engines with a ratio of about 6.0:1 (dry) would increase the overall thrust by 20%. This example would be similar to exchanging the F-404-400 with the EJ-200, which according to Reference 8 have very similar dimensions. 2) The extensive use of composite/advanced materials in a total redesign of the airframe, but still keeping the same shape and configuration. This could reduce the overall combat weight by as much as 20%, which Reference 9 would suggest to be quite reasonable for future aircraft. Finally, 3) the implementation of a TVC system allowing the aircraft to sustain post stall angles of attack up to 70°. It is assumed that the additional weight of the TVC system is negligible compared to the combat weight, and that there is no effect to the pitching moment of the aircraft due to the added weight at the rear of the aircraft.

To produce the NMA metric, a batch set of simulations of the manoeuvre was run. The simulations ran automatically, using flight control rules discussed in the previous section where the manoeuvre is described, to control the aircraft. Each of the three case studies was run independently. At each point in the altitude-velocity domain, the values were compared to the baseline, and the differences were plotted to show what advantage or disadvantage may come from the addition of a technology. The results are discussed below.

Results

Turning performance and energy performance are both of interest. This is discussed in Reference 10, and is referred to as *angles fighting* and *energy fighting* respectively. The former considers turn time and diameter, and the latter considers energy used in the manoeuvre and energy bleed at the end of the manoeuvre. For this reason, the following plots show turn time, turn diameter, energy consumption and bleed rate.

Baseline F/A-18a.

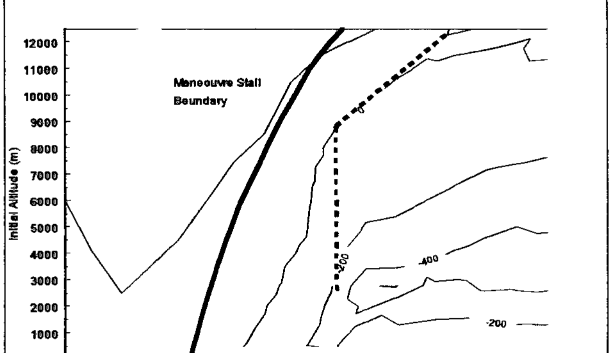

Figure 5 - Specific Excess Power Immediately after Turn Reversal, for the Baseline Aircraft.

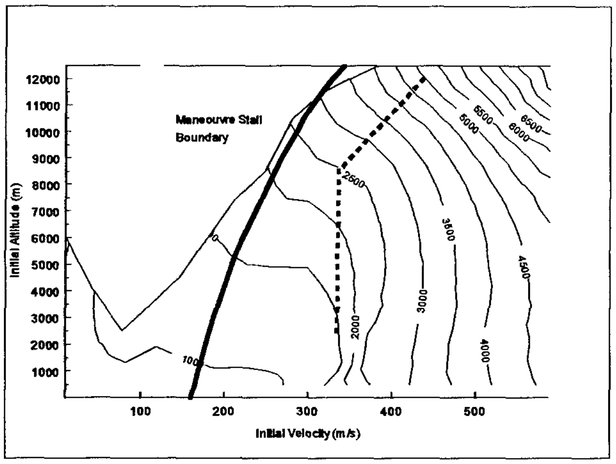

Figure 6 - Vertical Diameter in Metres at the End of the Turn Reversal, for the Baseline Aircraft.

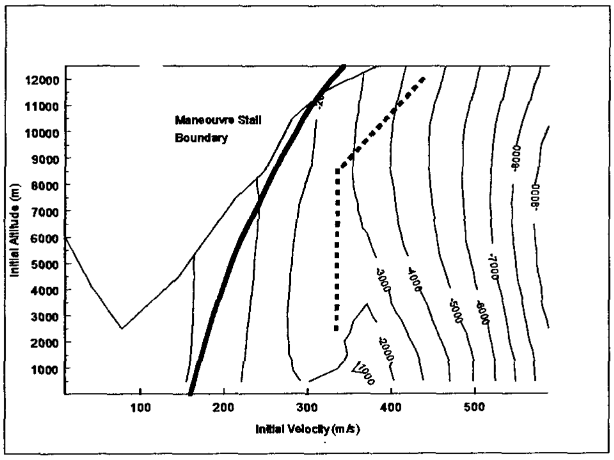

Figure 7 - Energy Gain During Turn Reversal, for the Baseline Aircraft.

Figure 4 shows the time to reverse the turn for the standard F/A-18a. Figures 5 and 6 show the Specific Excess Power (SEP) and the vertical diameter respectively for the standard aircraft. Figure 7 shows the energy gained during the manoeuvre. Values on Figure 7 which are negative, indicate that the aircraft has lost energy during the manoeuvre. These four plots can be used to work out the absolute performance of the three modified aircraft (if so desired), whose performance is shown in later figures. The thick black corner velocity line and the thick black dashed optimum line that exists on Figure 4 are also shown on Figures 5-7.

Case 1: Increase Thrust by 20%.

Figures 8-11 show the effect of changing the engines to increase the overall thrust by 20%. The figures have a thick black line drawn, which is the manoeuvre stall boundary for the standard F/A-18a, taken from Figures 4-7.

Also shown on Figures 8-11, is a thin black line which is similar in shape and position to the thick black line. This limit is the manoeuvre stall boundary for the modified aircraft. It is above the thick line (the standard aircraft), since the advanced technology allows the modified aircraft to turn at

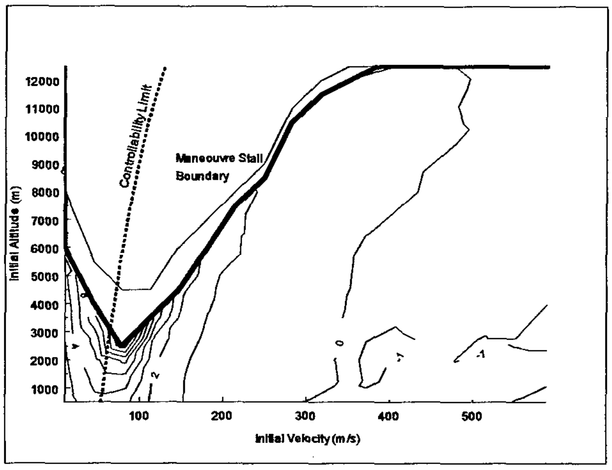

Figure 8 - Difference in Elapsed Time in Seconds to Complete Turn Reversal. Positive Values Show a Shorter Turn Time for the Aircraft with Increased Thrust.

higher altitude without stalling.

Also shown on these figures is a dashed line labelled 'Controllability Limit'. This is the line at which the aircraft is at 1g normal load factor with an AoA of 25°. This angle is deemed the maximum AoA at which the aircraft still has full pitch control, that is, the aircraft is still controllable.

Figure 8 shows contours evaluating the difference in time taken between the standard aircraft and the modified aircraft. Contours with positive values show where the modified aircraft has an advantage in turn time (at any speed to the left of the zero second contour). It can be seen that the maximum amount of time advantage that the modified aircraft has, is about 7 seconds, at just slower than 100m/s velocity and about 2500m altitude. Note though, that this is very close to the controllability limit of the aircraft. It is arguable that no pilot would want to prolong combat in this region and so generally, for the majority of the flight envelope, there is not more than about a second of advantage conferred by increasing the thrust of the engines.

At higher speeds, the modified aircraft appears to have a small disadvantage. However, this result would tell the pilot that at higher speed, the throttle should be reduced in order to reduce the turn time. The turn time would be reduced since the aircraft would slow to the corner velocity quicker, and hence have a higher average turn rate. It should be noted that the simulations were run using full throttle. It was not an objective to optimise the turn with throttle scheduling. However, this example shows that NMA could be used for such a purpose.

Figure 9 shows the SEP difference at the end of the turn reversal. It shows that there is virtually no difference between the two aircraft, except for the 200m/s bubble. At the speed and altitude where the 200m/s bubble exists, the standard aircraft is losing about 200 or more metres of energy height every second. Hence the modified aircraft is maintaining its energy at the end of the turn. This not only means that it is capable of sustaining a continued turn, but also that since less energy was used during the manoeuvre, there is a larger

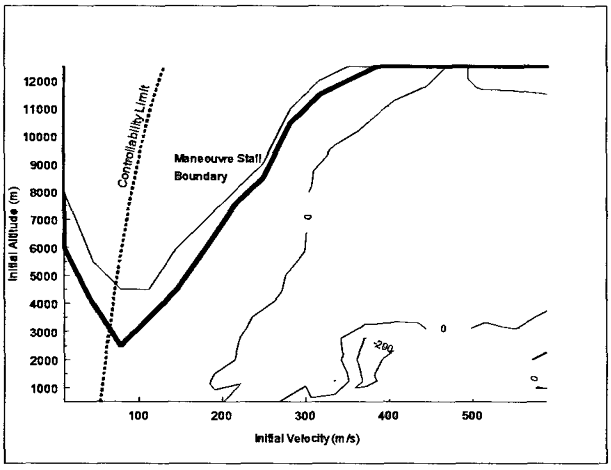

Figure 9 - Difference in Specific Excess Power Immediately after Turn Reversal. Negative Values Show Less Bleed Rate for the Aircraft with Increased Thrust.

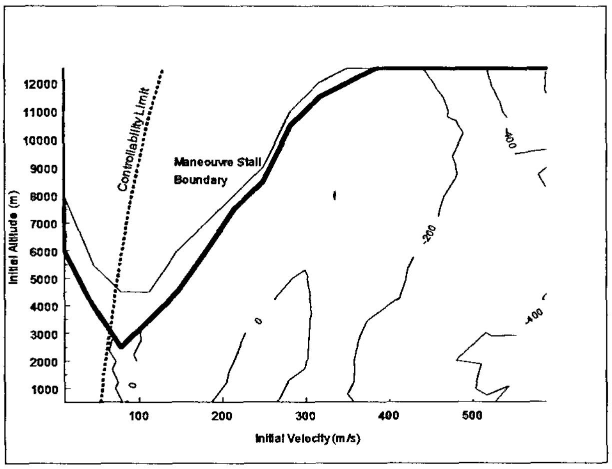

Figure 10 - Difference in Vertical Diameter in Metres at the End of the Turn Reversal. Positive Values Show a Smaller Turn Diameter for the Aircraft with Increased Thrust.

choice of follow on manoeuvres available.

Figure 10 shows the difference in the vertical diameter between the two aircraft. The modified aircraft has a small disadvantage (its turn diameter is typically less than 10% larger when compared to Figure 6 for any speed or altitude). However, for Figure 8 it was stated that thrust could be reduced at higher speed. If this were done, then the turn diameter would reduce, hence equalising any disadvantage shown in Figure 10.

Figure 11 shows the difference in energy gained/lost during the turn reversal. It shows that for higher speeds, the modified aircraft loses slightly less energy height, with the difference between the two aircraft no greater than 800m. Since the modified aircraft has more thrust, it will lose less speed during the turn, leaving it with more energy at the end.

Figures 8-11 show that increasing the thrust by as much as 20% only has a small effect on the performance of the aircraft for the vertical turn manoeuvre. NMA shows that for the modified aircraft there is not much advantage in SEP at the

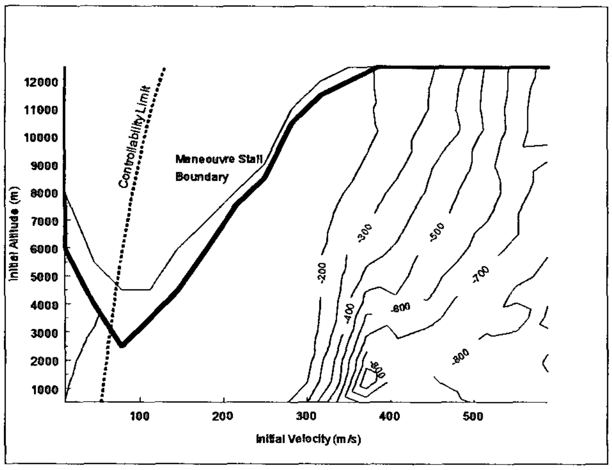

Figure 11 - Difference in Energy Used During Turn Reversal. Negative Values Show Less Energy Used by the Aircraft with Increased Thrust.

end of the manoeuvre, and that there is no real turn diameter disadvantage (less than 10%). The most advantage that comes is from the energy loss during the turn reversal. The modified aircraft has more thrust. This can be used to overcome the drag, and leave the aircraft with more energy at the end of the manoeuvre. Consider equation 1 below.

$$SEP = \frac{V[T\cos(\alpha) - D]}{W} \qquad \text{Equation 1}$$

where, V is velocity, T is thrust, D is drag, and W is weight. This equation is integrated over time to give the energy used during the manoeuvre. At low angles of attack (at which the manoeuvre is performed at high speeds due to the load factor limit), it is dominated by the thrust term, and hence increasing the thrust will reduce the energy used during the manoeuvre.

The high speed, high altitude regime, which is a typical BVR scenario, shows that although there is no turn advantage (in terms of turn time or diameter), there are quite large energy savings made, by increasing the thrust. BVR is dominated by the ability to continue turning without losing energy, and increasing the thrust helps to allow the aircraft to do this.

At low speed near the controllability limit (but above 120m/s), there are no advantages for the increase in thrust. Hence, to increase the WVR performance (which is typically at low speed and low altitude), a much greater thrust increase is required.

<u>Case 2: Decreasing Weight by 20%.</u>

Figures 12-14 show the effect on performance of reducing the combat weight of the aircraft by 20%. The thin black line above the thick black boundary in Figure 12 shows that a reduction in combat weight would mean that the modified aircraft could fly vertical turn reversals at higher altitude while at speeds less than 375m/s. As before, a controllability limit is shown as a dashed line. At any initial speed, the advantage of the modified aircraft increases with increase in altitude. The maximum advantage occurs near the manoeuvre stall boundary and lies between 5 and 10 seconds, for any

initial speed. This is an advantage of around 30% for all speeds, compared to the baseline aircraft. For WVR, an advantage of more than 5 seconds would be enough to obtain a shoot solution, before the enemy can return fire. The figure also shows that at low altitude and high speed, the standard aircraft gains the advantage. This is because the heavier aircraft will slow down quicker and get to its corner velocity sooner. The advantage is however very small, and unlikely to be significant.

Since the modified aircraft will not gain a time advantage from flying low and fast, the difference in SEP is not significant, and hence no plot is shown. The difference in SEP at the end of the manoeuvre is very similar to that for the first case study.

Figure 13 shows the change to the turn diameter. The higher the aircraft flies, the more of an advantage the modified aircraft gets. The maximum is as much as 1km, which is about 15% less than that of the standard aircraft. At low altitude and high speed, there is an advantage for the standard aircraft. This is again because the heavier aircraft will slow

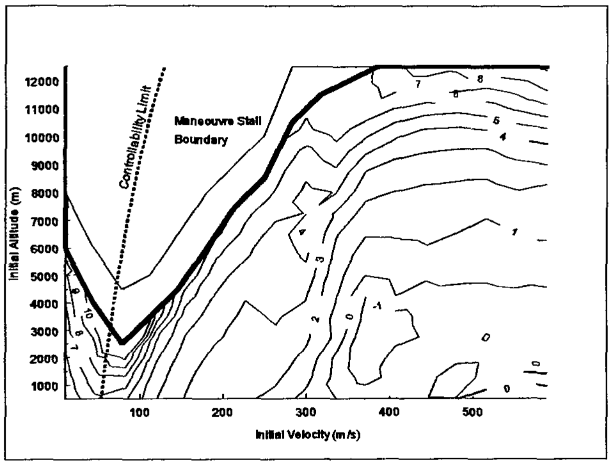

Figure 12 - Difference in Elapsed Time in Seconds to Complete Turn Reversal. Positive Values Show a Shorter Turn Time for the Aircraft with Decreased Weight.

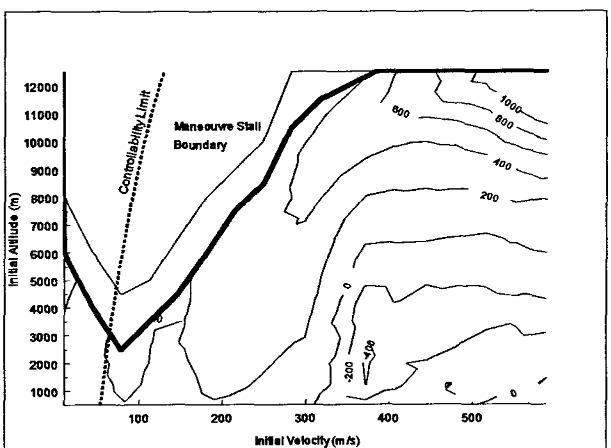

Figure 13 - Difference in Vertical Diameter in Metres at the End of the Turn Reversal. Positive Values Show a Smaller Turn Diameter for the Aircraft with Decreased Weight.

quicker and hence reduce the turn diameter. However, the modified aircraft could match this by reducing thrust as it enters the manoeuvre, although this would not give any time or diameter advantage. To maximise its superiority, the modified aircraft would do much better to fly as high as possible, while still being able to reverse the turn in the vertical plane.

Figure 14 shows the difference in the energy used during the turn reversal. In the areas where there is a time and diameter advantage for the modified aircraft (that is, near the manoeuvre stall boundary), there is also a small energy disadvantage shown by the +200m contours. However, at medium to low altitude and high speed (to the right and below the zero energy contour), the modified aircraft loses significantly less energy than the standard aircraft (up to 1400m less).

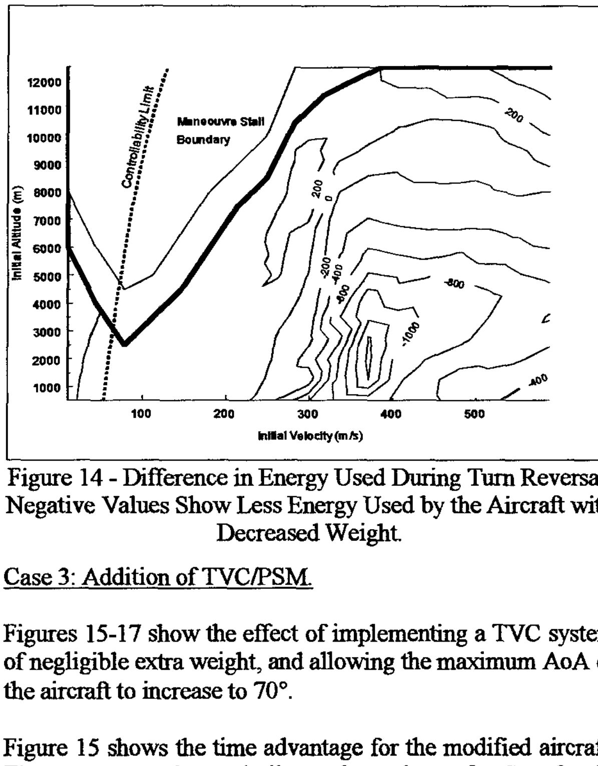

Figure 14 - Difference in Energy Used During Turn Reversal. Negative Values Show Less Energy Used by the Aircraft with Decreased Weight.

Case 3: Addition of TVC/PSM.

Figures 15-17 show the effect of implementing a TVC system of negligible extra weight, and allowing the maximum AoA of the aircraft to increase to 70°.

Figure 15 shows the time advantage for the modified aircraft. The contour trends are similar to those shown for Case 2. As with the case study for reduced weight, the biggest advantage to the TVC/PSM aircraft lies close to the manoeuvre stall boundary. The advantage decreases as altitude is decreased. The maximum advantage is again up to 10 seconds, with a minimum of 3 seconds for all speeds, as long as altitude is adjusted. Although it is not shown directly, comparing Figures 12 and 15 shows that the TVC/PSM aircraft has a minimum of a 3 second advantage over the lighter aircraft for most of the flight envelope. At lower speed, the advantage would fall to the lighter aircraft.

Returning to the comparison between the standard aircraft and the TVC/PSM aircraft, it is seen from Figure 15 that the standard aircraft will never have a time advantage. At low altitude and high speed, both aircraft will be load factor limited throughout the manoeuvre. This means that the modified aircraft will not be allowed to go to post stall AoAs,

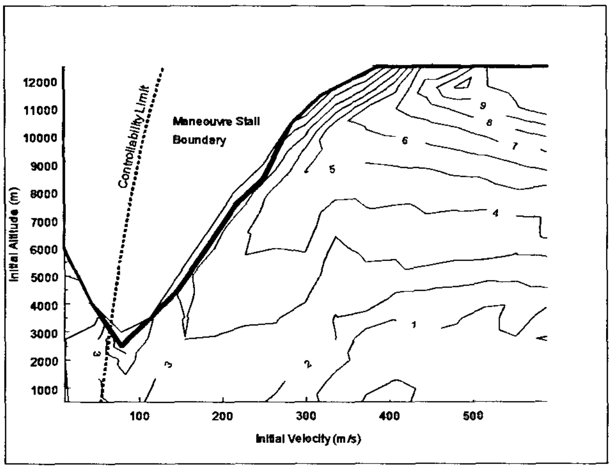

Figure 15 - Difference in Elapsed Time in Seconds to Complete Turn Reversal. Positive Values Show a Shorter Turn Time for the TVC/PSM Aircraft.

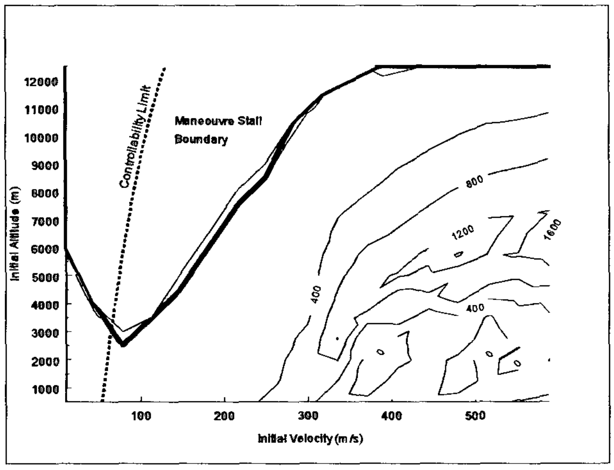

Figure 16 - Difference in Specific Excess Power Immediately After Turn Reversal. Negative Values Show Less Bleed Rate for the TVC/PSM Aircraft.

and so it will gain no advantage in having this technology. Conversely, the standard aircraft will have no advantage in turn time, and best that it can do is to fly low and very fast, reducing the performance difference to zero.

Figure 16 shows the SEP difference between the two aircraft at the end of the manoeuvre. It shows that the modified aircraft will have as much as a 1600m/s disadvantage. In some cases, this will mean that the modified aircraft will be losing energy at more than twice the rate of the standard aircraft. This issue of losing a lot of energy quickly is characteristic of an aircraft using its PSM ability to the full.

When comparing the energy used during the manoeuvre, the standard and the modified aircraft have very similar results. This is because they are essentially the same aircraft until the very last segment of the manoeuvre where the modified aircraft will go to a post stall AoA. If the pitch acceleration and maximum AoA limit are high enough, it is theoretically possible for the TVC/PSM aircraft to use less energy than the standard aircraft, because it can complete the manoeuvre sooner. For this reason, energy used during the manoeuvre can be very similar when comparing a standard aircraft to a TVC/PSM aircraft. However, the very high AoA of the TVC/PSM aircraft at the end of the manoeuvre means that its energy bleed rate will be much higher, affecting the performance in the next few moments, after the initial manoeuvre is completed. This is why the SEP at the end of the manoeuvre is very important when looking at such aircraft.

Figure 17 shows that the turn diameter is as much as 20% smaller than the standard aircraft (high altitude and high speed), and also that it is as much as 10% smaller than the lighter aircraft (Case 2, not shown). The standard aircraft can only at best match this performance, by flying low and slow.

At very low speed, the modified aircraft would be able to cross to the left of the controllability boundary of the baseline aircraft. This is because the TVC will provide an increased pitching moment (and hence control power) independently of speed. The increase in control power will give the aircraft the

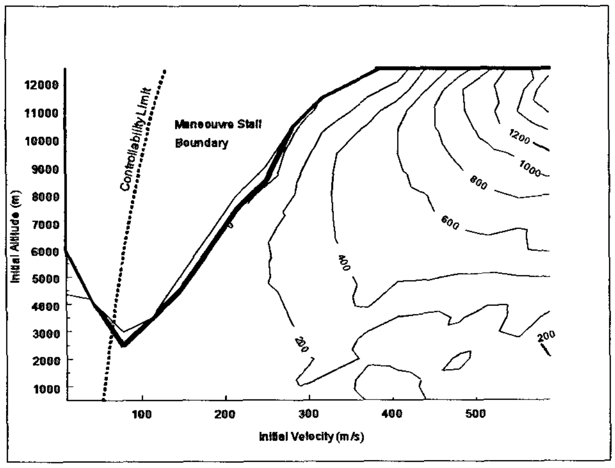

Figure 17 - Difference in Vertical Diameter in Metres at the End of the Turn Reversal. Positive Values Show a Smaller Turn Diameter for the TVC/PSM Aircraft.

capability to sustain much higher AoAs. Note though, that this very low speed and altitude is unlikely to be used by the pilot, since much greater advantages can be found in other parts of the flight envelope.

For the vertical turn reversal, the addition of TVC and PSM technologies to the aircraft can give very large time and diameter advantages, even in excess of those seen in Case 2 (reduced weight). However, the use of TVC/ PSM will not confer an energy advantage. The SEP at the end of the manoeuvre can be so negative that if a kill is not obtained, then the modified aircraft will be tactically in a very poor slow situation, in only a few seconds. Here, NMA allows the designer to see the trade off between energy and turn performance required for TVC/PSM aircraft.

Discussion of Case Studies

NMA results have been shown for three different case studies. These results show that conclusions could be drawn about the usefulness of the technologies. For the manoeuvre considered, the authors have not drawn any conclusions as to

which technologies are best. It is only intended to demonstrate that the results could be used in helping to determine appropriate levels of new technologies. Note that if NMA is to be used to determine benefits/disadvantages of new technologies, or simply for assessing the performance of aircraft, then a much fuller analysis than that shown here is required. For a fuller assessment, there are many more combat realistic manoeuvres that should be considered, for example horizontal turn reversal, and axial acceleration. When considering technology such as TVC/PSM, it should be realised that this technology provides a capability to execute many new manoeuvres. It is possible that some of these may have tactical relevance, and so these manoeuvres should also be analysed in the full assessment, as long as the limitations of the models used is appreciated.

Once all of the relevant manoeuvres have been considered, and the full analysis has been completed, conclusions can be drawn about where the aircraft is most manoeuvrable. These conclusions can then be used to develop tactics. On the other hand, the designer can determine where the aircraft is under performing, and can use the NMA to execute a parametric study to see what can be modified in the design to give performance closer to that desired.

Conclusions

The NMA metric clearly shows the advantages and disadvantages of different technologies used in the design of an aircraft. The results give values which have meaning to both designer and a pilot.

The results include the performance, the manoeuvrability and the agility of the aircraft, and cover the WVR and the BVR regimes. NMA considers realistic closed loop manoeuvres. This makes NMA a powerful tool for the conceptual or preliminary designer, especially for carrying out parametric studies on the overall combat performance.

NMA simplicity, allows performance assessment of aircraft, quickly and easily. This will aid in the overall aim of a reduction in design cycle time.

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